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Impact of atmospheric submonthly oscillations on sea surface temperature of the tropical Indian Ocean

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[1] Impacts of atmospheric intraseasonal oscillations (ISOs) at submonthly periods (10–30 days) on Indian Ocean sea surface temperature (SST) are studied using satellite observed outgoing long wave radiation, QuikSCAT winds, SST and an ocean general circulation model for the period of 1999–2004. The results suggest that submonthly ISOs can cause significant 10–30 day SST changes throughout the equatorial basin and northern Bay of Bengal, with an amplitude of as large as 0.5°C and standard deviation of exceeding 0.2°C for a 4-year record. Impact of the submonthly ISO associated with the Indian summer monsoon is separately examined. It is associated with basin-scale SST evolution with distinct spatial structures. The SST variation results mainly from submonthly wind forcing, which causes changes in oceanic processes and surface turbulent heat fluxes. Radiative fluxes can also have large influences in some regions for some ISO events. **Citation:** Han, W., W. T. Liu, and J. Lin (2006), Impact of atmospheric submonthly oscillations on sea surface temperature of the tropical Indian Ocean, *Geophys. Res. Lett.*, *33*, L03609, doi:10.1029/2005GL025082.

1. Introduction

[2] The quasi-biweekly mode (also called 10–20 day mode) and the Madden-Julian Oscillation (MJO) are two major intraseasonal oscillations (ISOs) in the tropics. They play equally important roles in causing "active" and "break" phases of Asian summer monsoon [*Lau and Waliser*, 2005, and references therein]. Recent modeling studies demonstrate that air-sea coupling on intraseasonal time scales can improve ISO phase and propagation [*Kemball-Cook and Wang*, 2001; *Fu et al.*, 2003], suggesting the importance of air-sea interaction to ISO dynamics. In fact, possible importance of air-sea interaction in the Asian summer monsoon region has led to two major field experiments over the Indian Ocean: the BOBMEX [*Bhat et al.*, 2001] and JASMINE [*Webster et al.*, 2002]. Results from these experiments, in conjunction with other observational evidence [*Sengupta et al.*, 2001b; *Harrison and Vecchi*, 2001; N. H. Saji and S.-P. Xie, personal communication, 2005], show large sea surface temperature (SST) changes associated with ISO events, with an amplitude of 2°C from peak cooling to peak warming.

[3] Investigation of SST variability is the first and key step toward understanding air-sea coupling mechanisms of ISOs. Most existing studies, however, either focus on effects of the MJO [e.g., *Jones et al.*, 1998; *Shinoda et al.*, 1998; *Woolnough et al.*, 2000; *Duvel et al.*, 2004]-which dominates 30–90 day oscillations (see *Madden and Julian* [1994] for a review), or examine the entire ISO band (10–90 day periods [*Sengupta et al.*, 2001b; *Schiller and Godfrey*, 2003]). It is not clear whether or not submonthly ISOs, which are dominated by the quasi-biweekly mode, have significant impacts on SST over the Indian Ocean region, although the biweekly mode is suggested to be the cause of the observed, strong meridional currents at 12–15 day periods in the equatorial region [*Reppin et al.*, 1999; *Sengupta et al.*, 2001a; *Masumoto et al.*, 2005; *Miyama et al.*, 2006]. Given that the MJO and quasi-biweekly mode have different dynamics [*Chatterjee and Goswami*, 2004], structure, and propagation [e.g., *Murakami and Frydrych*, 1974; *Krishnamurti and Ardanuy*, 1980; *Chen and Chen*, 1993], it is expected that they have different impacts on SST. Composite plots based on both submonthly ISO and MJO events may obscure the SST patterns associated with submonthly ISOs.

[4] The goal of this paper is to quantify the impact of submonthly ISOs on SST in the Indian Ocean, investigate the processes that cause the SST change, and examine the structure and amplitude of SST associated with the biweekly mode during Asian summer monsoon. Neither of these has been previously examined, yet they are important for understanding the coupled mechanisms of submonthly ISOs.

2. Data and Model

[5] The 3-day-mean SST from the Tropical Rainfall Measuring Mission (TRMM), satellite observed daily outgoing long wave radiation (OLR), and 3-day QuikSCAT winds [*Tang and Liu*, 1996] for the period of January 1999–November 2004 are analyzed. Because QuikSCAT winds begin in July 1999, ERA-40 winds are used before this time. The 3-day TRMM SST data have been demonstrated to adequately resolve intraseasonal oscillations, and they agree favorably with in situ observations [e.g., *Sengupta et al.*, 2001b; *Harrison and Vecchi*, 2001].

[6] The ocean general circulation model (OGCM) is the HYbrid Coordinate Ocean Model (HYCOM) configured to the tropical Indian Ocean north of 30°S, with a horizontal resolution of 0.5° × 0.5°, realistic bottom topography, and 18 vertical layers. Surface forcing fields used to force HYCOM are the 3-day QuikSCAT winds, net short wave and long wave radiation from the International Satellite Cloud Climatology Project flux data (ISCCP-FD [*Zhang et al.*, 2004]), CMAP pentad precipitation, NCEP air temper-

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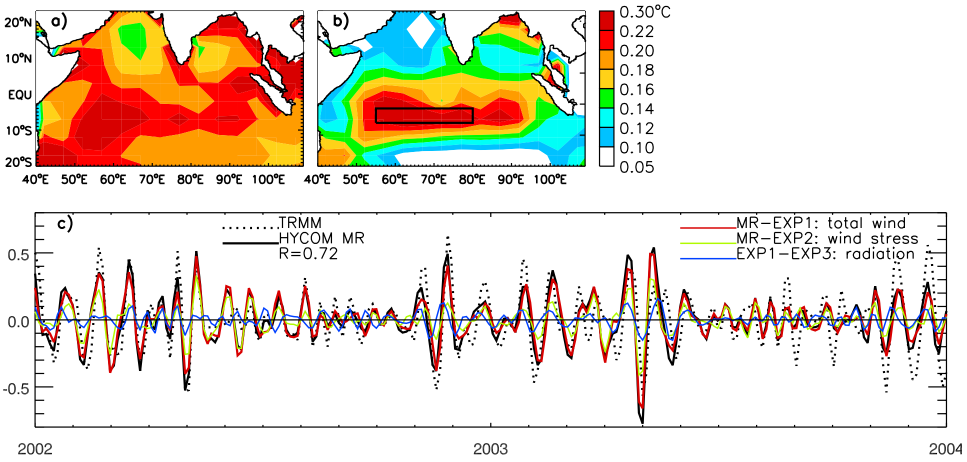

Figure 1. Standard deviation of 10–30 day bandpassed SST based on 2000–2003 record from (a) TRMM data and (b) HYCOM MR solution. (c) Time series of 10–30 day SST from TRMM and from an hierarchy of HYCOM solutions averaged over the boxed region shown in Figure 1b.

ature and specific humidity. NCEP winds are also tested, but SSTs forced by QuikSCAT winds agree better with TRMM data (not shown).

[7] The model is restarted from the HYCOM solution forced by ERA-40 fields [*Han*, 2005] on January 1, 1999, and integrated forward until November 2004. Four parallel experiments are performed. The main run (MR) is forced by the 3-day-mean fields, and is the most complete solution in the hierarchy. Experiment 1 (EXP1) is the same as the MR except for applying a lowpass 105-day filter on wind stress and wind speed. The difference solution, (MR−EXP1), estimates effects of intraseasonal wind stress and wind speed. Experiment 2 (EXP2) is the same as EXP1 except for only filtering wind stress, and (MR−EXP2) isolates influence of intraseasonal wind stress (which can cause intraseasonal SST through upwelling and advection). (EXP2-EXP1) estimates effects of intraseasonal wind speed (which can affect SST through turbulent heat fluxes and entrainment cooling). EXP3 is the same as EXP1 except for filtering all the forcing fields, and (EXP1-EXP3) mainly measures effects of intraseasonal short and long wave radiative fluxes.

[8] To isolate submonthly ISOs, a 10–30 day Lanczos digital filter is applied to wind, OLR, and SST fields. The filter employs 121 weights, giving very sharp cutoffs with negligible Gibbs oscillation (not shown) and thus effectively excludes the MJO [also see *Kiladis and Weickmann*, 1997].

3. Results

[9] The observed 10–30 day SST exhibits significant amplitudes in 10°S–10°N, northern Bay of Bengal, and southwestern Indian Ocean (Figure 1a). These spatial patterns are reasonably simulated by HYCOM (Figure 1b), albeit with some quantitative differences. Time series of the 10–30 day SST averaged over (55°E–80°E, 8°S–4°S), the boxed area in Figure 1b where the standard deviation is large, shows that SST variation can often reach 0.4∼0.5°C and occasionally exceed 0.5°C (dashed curve in Figure 1c). Amplitudes from peak cooling to peak warming can be 0.8∼1.0°C, which are approximately 30∼50% of the observed amplitudes for total intraseasonal SST [e.g., *Sengupta et al.*, 2001b; *Harrison and Vecchi*, 2001]. The 10–30 day SST caused by submonthly ISOs is comparable with the 30–90 day SST caused by the MJO, although the latter is often larger (not shown).

[10] The observed 10–30 day SST is reasonably simulated by HYCOM (compare dashed and dark solid curves in Figure 1c), with a correlation coefficient of 0.72 for a 2-year record (2002 and 2003) and 0.64 for a 4-year record (2000–2003). Both exceed 95% significance. To understand the processes that determine the SST change, the hierarchy of HYCOM experiments are examined. Evidently, submonthly winds (red curve) overall play a dominant role (compare with the dark solid), with a 4-year correlation of 0.97 between the two curves. Sometimes, however, radiative fluxes (blue) can have significant contributions (compare with dark solid), with a correlation of 0.59 between the two curves. The dominance of winds is contributed from both wind stress (green) and wind speed (difference between red and green). Similar analysis has been performed in various regions of the Indian Ocean, for instance the eastern equatorial warm pool, northern Bay of Bengal, south of India, and western equatorial basin. In all regions, winds (stress + speed) play a dominant role overall. In the warm pool and northern Bay, however, radiative fluxes can dominate over winds for some individual events.

[11] Does the quasi-biweekly mode associated with the “active” and “break” phases of Indian summer monsoon have significant SST signatures over the Indian Ocean? To answer this question, we first identify strong submonthly convection events over India, based on the 10–30 day OLR averaged over a base region (70°E–95°E, 10°N–25°N). This region is similar to the one used by *Sengupta et al.* [2001b] for the summer monsoon ISO, and meanwhile covers the base location used by *Krishnamurti and Ardanuy* [1980] for performing the biweekly mode composites. Nine strong events during northern summer (May–October) are identified for the period of 2000–2003. Wind and OLR composites for the 9 events are shown in Figure 2. Day 0 (middle) is chosen as the OLR minimum value in the base region exceeding 2 standard deviation. Fields of 3 days before and 3 days after the peak are shown in left and right panels.

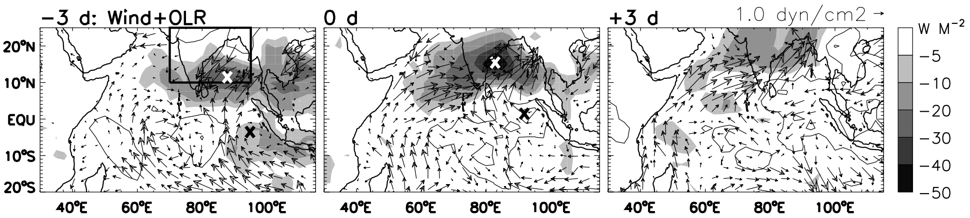

Figure 2. Composites of 10–30 day QuikSCAT winds and OLR based on 9 strong convection events in the boxed region (70–95°E, 10–25°N) during May–October.

[12] Interestingly, our composite winds and OLR remarkably resemble the quasi-biweekly mode of summer monsoon identified by *Chen and Chen* [1993], showing a double-cell structure in winds (marked by "x" in the left and middle panels) with both OLR and winds propagating northwestward. This close resemblance demonstrates that quasi-biweekly mode dominates the monsoon submonthly ISO. Indeed, the 10–30 day regressed winds against the base-region OLR for the entire 2000–2003 record are very similar to our wind composites, further demonstrating the dominance of the biweekly mode. Given this dominance, we refer to the monsoon submonthly ISO effect as the effect of quasi-biweekly mode.

[13] To reveal the spatial structure and amplitude of SST associated with the monsoon mode, the bandpassed SST corresponding to one of the 9 events that peaks in June 8, 2001, is shown in Figure 3. The SST composites for all 9 events have similar patterns but with weaker amplitudes. Evidently, the quasi-biweekly mode can cause basin-scale SST change with a distinct spatial structure. Prior to the event peak, the ocean warms up in the western-central basin and to a lesser degree northern Bay of Bengal; it cools in the eastern Indian Ocean warm pool region (left). During the event peak, cooling occurs in the Arabian Sea and western tropical basin, but warming appears in the eastern equatorial warm pool and central basin near 0–10°S (middle). The warming/cooling further enhance after the event peak (right).

[14] These SST changes result largely from forcing by submonthly winds (Figure 3, bottom), with wind stress and speed playing comparable roles (figures isolating effects of wind stress and speed are not shown). For example, wind speed is the major cause for the Arabian Sea warming before the event peak (not shown). This is because 6 days prior to the peak, submonthly winds in the Arabian Sea are northeasterlies (top-left), which weaken the seasonal southwest monsoon winds, reduce turbulent heat fluxes and entrainment cooling, and thus increase SST. As the event develops and moves northwestward, winds enhance in the entire western ocean and become southwesterlies in the Arabian Sea (top middle and right), cooling the western basin. In the warm pool region, submonthly winds weaken the seasonal southeasterlies right before and during the event peak, producing the warming. Meanwhile, wind stress

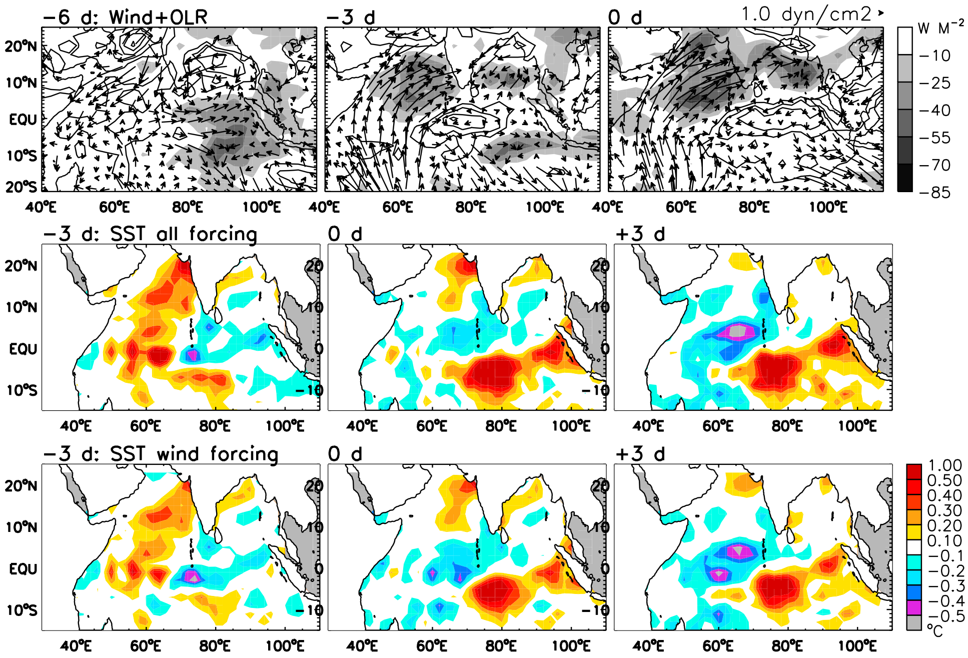

Figure 3. (top) 10–30 day QuikSCAT winds and OLR for one of the 9 events that peaked (day 0) on June 8, 2001. (middle) HYCOM 10–30 day SST from (MR-EXP3) for the event. SST change in this solution is caused by all mechanisms. (bottom) Same as top except for (MR-EXP1), which estimates the SST forced only by winds. Note that SST lags winds because it is the time derivative of SST that directly responds to winds.

enhances the SST changes by a comparable amount (not shown), via causing Ekman convergence (divergence), which reduces (enhances) upwelling cooling, and through changing horizontal advection. A detailed quantification of each process at different locations during different phases of events is out of the scope of this paper, but is an essential part of our ongoing research.

[15] Even though the winds dominate, radiative fluxes also contribute to the amplitudes (difference between middle and bottom panels). For example, they enhance the cooling in the eastern equatorial warm pool and southern Bay before and during the event peak, because convective clouds (negative OLR) reduce short wave radiation; in the western ocean, reduced convection (positive OLR) enhances the short wave radiation and thus strengthen the warming. Similar analysis is conducted for each of the 9 events, and overall we obtain similar results. In some regions for specific cases, however, radiative fluxes can be very important. During the event of June 2000, radiative fluxes dominate over winds in the northern Bay of Bengal.

4. Summary

[16] Data analysis combined with OGCM experiments for the period of 1999–2004 are utilized to quantify the impact of submonthly ISOs on Indian Ocean SST, and to estimate the processes involved. Effects of the submonthly ISO associated with the active and break phases of Indian summer monsoon, which is dominated by the quasi-biweekly mode (Figure 2), is specifically examined.

[17] Our results suggest that submonthly ISOs can cause significant 10–30 day changes in SST over the Indian Ocean, with a peak to peak amplitude of as large as 0.8∼1°C and a standard deviation for a 4-year record exceeding 0.2°C in some regions (Figure 1). This amplitude explains 30∼50% of the observed intraseasonal SST and is comparable with (although sometimes weaker than) the SST caused by the MJO. Submonthly winds are the major force for the SST changes overall (Figures 1c and 3). Both wind stress and wind speed play important roles. Radiative fluxes can also have large contributions in some regions for some events. The quasi-biweekly mode associated with the Indian summer monsoon (based on highly convective submonthly ISOs with OLR exceeding 2 standard deviation in the base region) is associated with basin-scale SST changes with a distinct spatial structure: with warming in the central-western Indian Ocean basin and northern Bay of Bengal, and cooling in the eastern equatorial warm pool as well as southern Bay before the event peak. The situation progressively reverses during and after the event peak. This structure is different from the SST pattern caused by the MJO [*Schiller and Godfrey*, 2003], which shows basin-wide warming before the event and cooling afterward. Results of this paper have important implications for air-sea interaction mechanisms of submonthly ISOs.

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